GW-Induced Freeze-In as Background-Mediated Collapse Admissibility

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Abstract

Recent work demonstrates that stochastic gravitational-wave (GW) backgrounds in the early universe can generate fermionic energy density through a mechanism known as gravitational freeze-in, overcoming the conformal protection of massless fermions by introducing structured perturbations into the spacetime background [1].

In this note, we reinterpret this mechanism within the framework of Quantum Collapse Geometry (QCG), proposing that GW-induced fermion production is not fundamentally a process of particle creation, but rather an instance of *background-mediated collapse admissibility.* In this view, stochastic gravitational waves act as a relational deformation field that modifies admissibility constraints, allowing previously suppressed fermionic configurations to emerge as stable, persistent sectors. This interpretation situates GW-induced freeze-in within the broader QCG principle that structure arises through selection under constraint.

1 Introduction

Standard cosmological treatments of particle production emphasize dynamical generation: fields evolve under background conditions, and excitations emerge through interaction or symmetry breaking. However, this perspective implicitly treats the space of possible configurations as continuously accessible.

Quantum Collapse Geometry (QCG), by contrast, distinguishes between:

- **Configuration space**: what is mathematically possible,
- **Admissible structure**: what can persist under constraint and collapse-selection.

Recent results on gravitational-wave-induced freeze-in provide a natural setting in which this distinction becomes physically explicit. In particular, it is shown that massless Weyl fermions are not produced in an expanding universe due to conformal symmetry, but that a stochastic GW background breaks this symmetry and enables fermion production [1].

We reinterpret this not as "production from nothing," but as a shift in admissibility structure induced by a background field.

2 Conformal Neutrality as Collapse Inadmissibility

In the absence of perturbations, Weyl fermions exhibit conformal symmetry, leading to vanishing energy density under expansion alone [1].

In QCG terms:

- the fermion sector exists in configuration space,
- but remains *collapse-neutral*, i.e., not selected into persistent structure.

This corresponds to a regime in which admissibility constraints eliminate net occupation, leaving the sector dynamically present but observationally absent.

3 Gravitational Waves as Admissibility-Breaking Fields

The introduction of a stochastic GW background modifies the metric:

$$ds^2 = -dt^2 + a^2(t)(\delta_{ij} + h_{ij})dx^i dx^j \tag{1}$$

and induces fermion–graviton interactions that generate nonzero fermion energy density [1]. In QCG, this corresponds to:

> a deformation of the relational constraint structure that renders previously inadmissible configurations collapse-accessible.

Thus:

$$\begin{aligned}\text{GW background} &\to \text{structured relational variation}\\ &\to \text{admissibility symmetry breaking}\\ &\to \text{collapse-selection into fermionic sector}\end{aligned}$$

3.1 Interpretation: Dark Sector as Admissibility-Decoupled Regime

The mechanism described above admits a natural interpretation in relation to dark sector phenomenology.

In the standard cosmological picture, dark matter is characterized operationally by its gravitational influence together with its absence of strong coupling to the visible sector. Within the present framework, this behavior arises generically from the structure of admissibility.

Recall that admissibility is governed by the coordination capacity $C[R]$, determined by effective coupling strength κ and persistence χ. A sector may therefore exist as a dynamically stable configuration under the collapse operator Φ while remaining weakly coupled to the dominant coordination regime associated with geometric observables.

Such sectors satisfy:

$$C_{\text{internal}}[R] \geq C_{\text{crit}}, \quad C_{\text{coupling}}[R_{\text{visible}} \leftrightarrow R] \ll C_{\text{crit}}.$$

That is, internal coordination is sufficient for stability, but cross-sector coordination is insufficient to produce observable interaction.

From this perspective, dark sectors correspond to *admissibility-decoupled regimes*: relational configurations that are collapse-stable but fail to maintain sufficient coordination with the visible geometric layer to participate in standard interaction channels.

The GW-induced freeze-in mechanism provides a concrete realization of this structure. Background fields modify κ and χ, shifting the admissibility landscape so that previously suppressed configurations become stable. However, the same conditions that enable their stabilization do not generically guarantee strong coupling to the visible sector.

As a result, such configurations can persist and contribute to the overall energy density of the universe while remaining observationally suppressed, matching the defining features of dark matter.

This interpretation does not introduce new entities beyond those already implied by the admissibility structure. Rather, it identifies dark sector phenomenology as a natural consequence of coordination-limited interaction across regimes.

Observational Consequences. If dark sector phenomenology reflects admissibility-decoupled regimes, then observable signatures should track variations in coordination rather than solely particle-specific properties. In particular, background-dependent shifts in effective coupling—such as those induced by stochastic gravitational-wave fields or evolving cosmological conditions—may modulate the abundance and activation thresholds of dark sectors, leading to deviations from strictly constant freeze-in yields. Additionally, partial or transient coordination between sectors could produce weak, scale-dependent imprints in structure formation, appearing as small departures from collisionless cold dark matter behavior without requiring direct interaction channels. More generally, this framework predicts that observability itself is contingent: sectors may transition between effectively "dark" and weakly coupled states as the coordination landscape evolves, suggesting that dark matter phenomenology may exhibit subtle environmental or epoch-dependent variation. This perspective motivates re-examination of observational datasets sensitive to small-scale structure, cosmological initial conditions, and stochastic gravitational-wave backgrounds, where coordination-dependent effects may produce subtle but systematic deviations from standard expectations.

4 Spectral Structure as Collapse Geometry

The GW background is modeled by a broken power-law spectrum with characteristic scales:

$$q_{\rm min} \sim H_*, \quad q_{\rm peak}, \quad q_{\rm max} \tag{2}$$

The resulting fermion abundance depends strongly on this structure [1].
Within QCG:

- the GW spectrum defines a *collapse-driving geometry in frequency space*,
- admissibility is scale-dependent,
- only specific spectral regions induce stable occupation.

5 Temporal Coherence and Collapse Persistence

The fermion production rate depends on the unequal-time correlator:

$$\langle h_q(\tau'') h_q^*(\tau') \rangle \tag{3}$$

with coherence encoded in a function $\gamma_q(\Delta\tau)$ [1].
In QCG terms:

- coherence corresponds to persistence across collapse cycles,
- incoherence corresponds to rapid loss of structural reinforcement.

Thus, collapse is sensitive not only to perturbation amplitude, but to temporal coherence of constraint deformation.

6 Gauge-Trivial Modes and Collapse Resolution

Long-wavelength GW modes do not contribute to fermion production because they can be absorbed into coordinate transformations [1].
In QCG:

- these modes are *admissibility-trivial*,
- they do not introduce real distinctions at the relevant scale,
- they lie below the collapse resolution threshold.

7 Freeze-In as Collapse-Stabilized Sector Formation

The produced fermions initially behave like radiation:

$$\rho_\psi \propto a^{-4} \tag{4}$$

and later, upon acquiring mass, contribute to dark matter [1].
In QCG:

- early phase: admissible but non-massive sector,
- later phase: reclassification under new constraints,
- result: persistent matter sector.

This suggests that dark matter may represent a fossilized collapse-selected sector stabilized under evolving constraint regimes.

8 Synthesis

The GW-induced freeze-in mechanism can be summarized as:

> A stochastic gravitational-wave background acts as a relational deformation field that breaks conformal admissibility constraints, allowing fermionic configurations to enter collapse-stable sectors, with abundance governed by the spectral and temporal coherence structure of the background.

9 Relation to Existing Selection Frameworks

The interpretation presented here is consistent with several established mechanisms:

- **Decoherence and einselection:** environmental interaction selects stable pointer states.
- **Renormalization group:** only relevant operators persist under scale transformation.
- **Thermodynamic selection:** stable macrostates emerge under dissipative constraint.

The QCG perspective differs in treating this selection process as generative rather than descriptive.

10 Implications for QCG

1. Backgrounds define admissibility, not just dynamics.
2. Particle production reflects selection from latent configuration space.
3. Collapse is spectrally mediated.
4. Coherence governs persistence.
5. Cosmological structure encodes collapse history.

10.1 Collapse-Admissibility Functional (Conceptual Form)

We may schematically represent admissibility as a functional:

$$\mathcal{A}[\psi; \mathcal{B}] = \int d\mu \; W_{\mathcal{B}}(x) \, |\psi(x)|^2 \tag{5}$$

where $\mathcal{B}$ denotes the background structure (here, the GW field), and $W_{\mathcal{B}}$ encodes the constraint deformation induced by the background.

Collapse-selection corresponds to the restriction:

$$\mathcal{A}[\psi; \mathcal{B}] > \mathcal{A}_{\text{crit}} \tag{6}$$

Only configurations satisfying this condition persist as observable structure.

11 Conclusion

Gravitational-wave-induced freeze-in provides a cosmological realization of a general QCG principle:

> Structure emerges when constraint deformation renders new sectors admissible to collapse-selection.

This perspective suggests that particle production mechanisms may, in general, reflect shifts in admissibility rather than the creation of new degrees of freedom.

If so, cosmological structure formation is not purely dynamical, but partially selection-driven, encoding the constraint history of the early universe.

This interpretation does not alter empirical predictions, but suggests that future probes of gravitational wave backgrounds and dark matter abundance may indirectly test the role of background-induced admissibility structure.

References

[1] Azadeh Maleknejad and Joachim Kopp. "Gravitational-Wave Induced Freeze-In of Fermionic Dark Matter". In: *Phys. Rev. Lett.* 136 (13 Mar. 2026), p. 131501. DOI: 10.1103/lr69-45v8. URL: https://link.aps.org/doi/10.1103/lr69-45v8.